A new magnetic field integral measurement system

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Abstract

In order to characterize the insertion devices at the Advanced Photon Source (APS) more efficiently, a new stretched coil magnetic field integral measurement system has been developed. The system uses the latest state-of-the-art field programmable gate array (FPGA) technology to compensate the speed variations of the coil motions. Initial results demonstrated that the system achieves a system measurement accuracy of 0.15 Gauss centimeter (G-cm) in a field integral measurement of 600 G-cm, probably the world's best accuracy of its kind.

1. Introduction

Insertion devices (IDs) at the Advanced Photon Source (APS) are characterized and fine tuned against their design specifications at the Magnetic Measurement Laboratory before installation into the storage ring [1]. A rotation wire/stretched coil system is used to measure the ID magnetic field integrals [2]. During each scheduled accelerator maintenance period, as a result of radiation damage, specific IDs have to be pulled out and retuned back to their original design specifications. Due to the time constraints of the maintenance period, we wanted to design a system that achieves the highest accuracy possible to reduce the characterization time [3]. The new APS ID field integral measurement system consists of a set of a long coil supported by two automated 4-axis stages W, X, Y, and Z. The new system has the following operation modes [4]:

1. Rotation Coil
   a. First field integral (horizontal and vertical) measurements.
   b. Second field integral (horizontal and vertical) measurements.
   c. Multipole components of first field integral measurements.

2. Translation Coil
   a. Multipole components of first field integral measurements.

3. Stretched Wire
   a. First field integral (horizontal and vertical) measurements.
   b. Second field integral (horizontal and vertical) measurements.

With the latest state-of-the-art field programmable gate array (FPGA) technology, the system is capable of synchronized measurements of position (0.005 degree/0.5 micron in resolution), time (25 ns), and voltage (16 bit), which yields a system measurement accuracy of 0.15 Gauss centimeter (G-cm) in a field integral measurement of 600 G-cm, that is 2.5×10^{-4}.

2. Theory of operation

Stretched coil magnetic field integral measurement is a very powerful way of characterizing the ID field integrals. The APS field integral measurement system is designed to verify that the field integrals of the IDs meet or exceed their specifications before their deployment or redeployment. The system is based upon the following theory of operation. The coordinates are shown in figure 1.
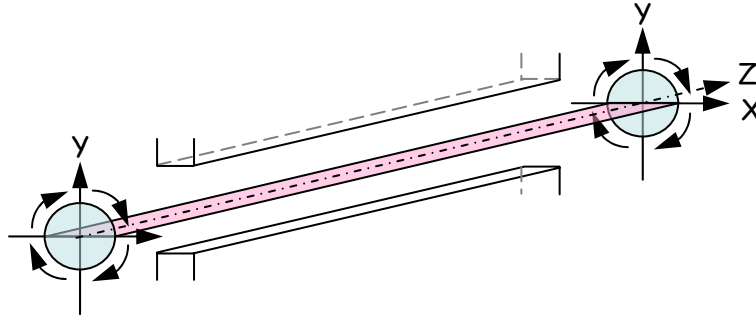

Figure 1. Schematic diagram of the stretch coil stages.

1. First Field Integrals of the Coil Rotation Mode

   Magnetic flux time dependence over the area of rotating coil is defined by the expression:

$$\Phi_y(t) = d * \cos\varphi \int_{-L/2}^{L/2} B_Y(z)dz = \overline{B_y} * L * d * \cos\varphi = J1_y * d * \cos\varphi$$

$$\Phi_x(t) = d * \sin\varphi \int_{-L/2}^{L/2} B_x(z)dz = \overline{B_x} * L * d * \cos\varphi = J1_x * d * \cos\varphi$$

$$\varphi = \left(\frac{2\pi}{T}\right) * t,$$

   where $\overline{B_x}$ and $\overline{B_y}$ are averaged over Z components of the magnetic field, L is the coil length, d is the coil width and T is rotation period, $J1_x$ and $J1_y$ are first field integrals.

   This expression is valid when field integral change over the width of the coil (5 mm in our case) and is small enough to allow the fitting to sinusoidal function.

   Signal from coil:

$$U(t) = -N * \frac{\partial \Phi}{\partial t} = J1_y * d * N * \frac{2\pi}{T} * \sin\varphi - J1_x * d * N * \frac{2\pi}{T} * \cos\varphi, \qquad (1)$$

where N is the number of coil turns. First field integrals can be found from the above expression by integrating the signal and fitting the flux dependence on the time.

2. Second Field Integrals of the Coil Rotation Mode

One end of the coil is rotated by 180° to perform these measurements (8-shape coil).

$$\Phi_y(t) = \Theta * \cos\varphi \int_{-L/2}^{L/2} B_y(z) * z\,dz$$

$$\Phi_x(t) = \Theta * \sin\varphi \int_{-L/2}^{L/2} B_x(z) * z\,dz$$

$$J2_{x,y} = \pm\frac{\Phi_{x,y}}{\Theta} + \frac{L}{2} J1_{x,y}, \qquad (2)$$

where + in expression (2) corresponds to rotation of the 2nd stage by 180°, − for rotation of the 1st stage, $\Theta = \frac{2d}{L}$.

Flux is defined the same way as for the first field integrals, and the second field integrals are defined from equation (2).

3. Coil Translation Mode

In translation mode, the coil moves in the X direction and measures flux difference from the initial value. The orientation of the coil is vertical to measure the horizontal component of the field integral, and horizontal to measure the vertical component of it. This option is preferable for multipole component measurements.

Magnetic flux time dependence:

$$\Phi_{x,y}(x) - \Phi_{x,y}(0) = \Delta J1_{x,y} * d = -\frac{1}{N}\int_0^x U_{x,y}(x)dx(t). \qquad (3)$$

4. Single Stretched Wire Translation Mode

Only one side of the coil is moving with this option, so the area of the coil is changing with time. Usually this mode is used for measurements of only the vertical component of the first field integral due to limitation in space for the Y direction.

$$\Phi_y(x_i) = J1_y(x_i) * (x_i - x_{i-1}) = -\frac{1}{N} \int_{x_{i-1}}^{x_i} U_{x,y}(x) dx(t).$$

This option is preferable for first field integral measurements and does not require averaging over half an undulator period, because imperfection of the wire does not affect the result in this case.

Measurements of second field integrals have to be performed with cross motion of the ends: i.e. while one end of the coil moves from – maximum position to + maximum X position, other end moves in opposite direction from + maximum X position to – maximum X position. Flux $\Phi_y(x_i)$ is defined in the same way as for first the field integral, where position x_i corresponds to the end of the wire and should be divided by $2*(x_i - x_{i-1})/L$, instead of $2*d/L$, as in (2).

An option of moving only one end of the wire is possible. Change of the angle Θ has to be taken into account in this case.

3. System Description

The field integral measurement system consists of the following subsystems:

1. A measurement coil made with 10-strand Litz wire. The coil is spring loaded onto a set of coil holders mounted on rotary tables. The spring constant is about 10 N/cm.

2. Two sets of precision rotary positioning stages, equipped with rotary encoders, each with a spring-loaded coil holder, remotely controlled by servomotors. The rotary encoder has a 20 mm hole on the shaft that allows the coil to go through. The encoder has 360 degrees of freedom with a 0.005 degree resolution. The rotary encoder is used to accurately define the angular position of the coil. The stages are mounted on precision linear positioning stages.

3. Two sets of 3-axis precision linear positioning stages, with linear encoders, remotely controlled by servomotors. The linear encoder has 0.5 micron resolution and is used to define the linear position of the coil.

4. A differential DC signal amplifier with low-pass signal filter and auto zero suppression. The signal conditioner pre-amplifies the coil signal ~3,000 times. The amplified signal is then fed to the 16 bit digitizer of an FPGA card.

5. The FPGA reconfigurable data acquisition card has eight 16 bit resolution analog inputs, 96 digital inputs/outputs, 25 ns time resolution, and 80 KB onboard memory. The digital I/Os are programmed to read the encoder positions. The analog inputs are configured to measure the coil signals synchronized with the position readouts and the time durations in real-time.

6. A PXI shelf with a control card that hosts the FPGA card and the software program.

4. System Control, Data Acquisition and Analysis

LabVIEW-based system software has been developed to coordinate the stage control and data acquisition. Figure 2 shows the schematic layout of the system control and data acquisition architecture. The system can be accessed via the Internet from anywhere anytime, wired or wirelessly, through the embedded http interfaces inside LabVIEW.
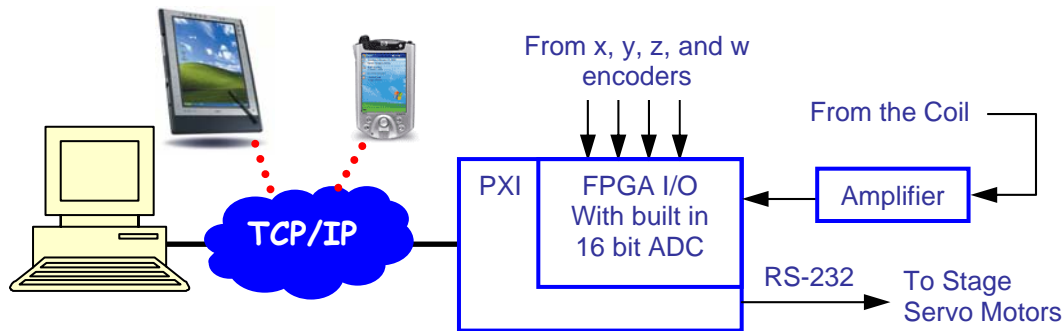

Figure 2. System control and data acquisition architecture schematic layout.

The system software has a Main Interface and following main modules and sub-modules:

1. The advanced motion control module fine tunes the stage positions and encoder readouts. It has one submodule, the motor velocity and acceleration control and monitoring. The submodule sets and monitors the velocity and acceleration parameters of all eight servomotors.

2. The integral average measurement module automates coil rotation integral measurements average over ID half period, $Z=0$ and $Z=\lambda/2$. It is necessary to average the measurements over the ID half period because of the unevenness of the coil width along the Z direction. The module rotates the stretched coil and sets the FPGA hardware to wait for the coil angular position to go to zero. When the angular position hits the zero mark, the hardware will simultaneously write the following data to its memory on fly:
   a. The angular positions of the coil with a settable angular resolution (down to 0.1 degree per step.)
   b. The integrated coil voltage signals across each angular step with a rate of 4.3 μs per sample at 16 bit resolution.
   c. The number of samples integrated within each angular step.

5

     d. The time duration within each angular step.

Until the coil angular position reaches the 360 degree mark, the hardware sends an interrupt to the module. The module then reads the data and sets the hardware to start another scan. Meanwhile it integrates the signal, fits the integrated data with a sinusoidal function to extract the field integral components, and plots the raw data along with the fittings.

After the measurements at Z=0 finishes, it sets the coil to the Z=λ/2 position, repeats the measurements, and averages the field integral measurement results at the two Z positions. The module records all the measured raw data, along with the real-time analysis results and other parameters into a file for later analysis and presentation.

The module has one submodule, the Integral Average Measurement Analysis and Plot. The submodule reads the saved data file, analyses the data, and plots the raw data along with the fittings and analysis results.

3. The integral multimeasurement module synchronizes multiple coil rotation integral measurements across the X axis. It carries out rotation integral measurements at certain X positions, extracts the field integral components, plots the components against the X axis, and moves on to the next X position and repeats the rotation integral measurement…. The module records all the measured raw data, along with the real-time analysis results and other parameters into a file for later analysis and presentation.

The module has one submodule, the Integral Average Measurement Analysis and Plot. The submodule reads the saved data file, analyses the data, and plots the raw data along with the fitting and analysis results.

4. The integral translation measurement module orchestrates coil translation integral measurements along the X direction. When the translation position hits the start position on the X stage, the FPGA hardware will simultaneously write the position, voltage, number of samples integrated within each linear step, and the time duration within each step to its memory on fly. Till the coil angular position reaches the finish mark, the FPGA sends an interrupt to module. The module then reads the data and sets the hardware to start another scan. Meanwhile it integrates the signal, fits the integrated data with a polynomial function to extract the field integral components, and plots the raw data along with the fittings.

The module has one sub module, the Integral Translation Measurement Analysis and Plot Sub-module. The sub module reads the saved data file, analyses the data, and plots the raw data along with the fitting and analysis results.

5. The system parameter database consists of three copies in a single file, the Current, the Backup and the Default. The Default copy is read only. Each copy contains, among others, the motor velocities, accelerations, voltage amplification

and system normalization constants, coil parameters, encoder reference indexes, encoder resolutions, stage gear ratios, motor velocity ratios, motor acceleration ratios, and motor resolutions. The system parameter database control module and its advanced system parameter database control module manipulate and manage the system parameter database.

6. The integral measurement FPGA firmware module resides on the FPGA reconfigurable card. It monitors the positions of the encoders, samples the coil voltage, the number of samples, and the durations of time. It also interfaces with the measurement modules and submodules. The FPGA module executes all the tasks in parallel at the speed of 40 MHz.

Each module and submodule has its own GUI interface except the FPGA firmware module. The main interface provides an access interface to all the main modules and hence the submodules. It checks the status of the FPGA reconfiguration data acquisition. If the FPGA card is not initialized or is running on different firmware, the module will download and initialize the card with the appropriate firmware. It also checks the status of all eight servomotors. If the motors are not initialized, it will try to re-initialize the motors.

5. Measurement results and discussion

A typical earth magnetic field integral measurement taken with the Integral Average Measurement Module is shown in Figure 3. It is displayed in the Integral Average Measurement Analysis and Plot submodule. The File Header field shows the basic parameters of the measurement. The coil was 4.2 meters long and 5 mm wide with 20 loops. The W rotation speed was 0.3 revolutions per second. The Integral plot field shows a specific integrated raw scan along with its sinusoidal fitting. Next to the Integrals field are the fitting parameters to that specific measurement. According to equation (1) in the theory of operation section, the sine component represents the X component of the field integral while the cosine component represents the Y component. The X and Y Components field displays the X and Y components of all five scans. To the right are the mean component values and the standard deviations over the five scans. The two fields at the bottom show the component averages over Z=0 and Z=1/2 λ. The standard deviation of the Y component over the five scans represents the system measurement accuracy of 0.08 G-cm over the mean value of the component of 189 G-cm, that is better then 5×10^{-4}.
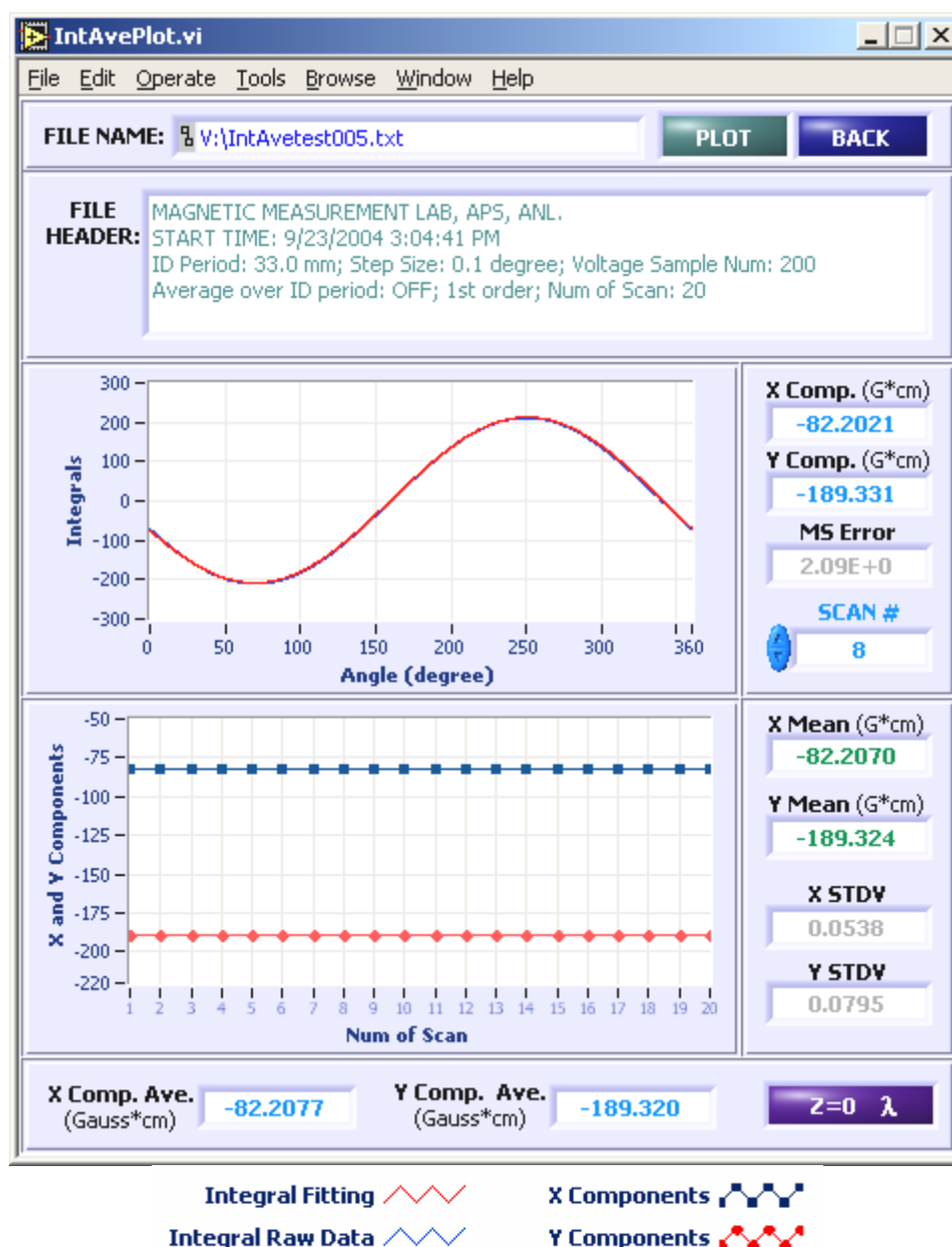
Figure 3. Earth magnetic field integral measurements.

Figure 4 displays a permanent magnet field integral multimeasurement across the X direction in rotation mode. The results are exhibited in the integral multimeasurement analysis and plot submodule. The File Header field shows the basic parameters of the measurement. The Integral plot field shows a specific integrated raw scan along with its sinusoidal fitting at a specific X position. Next to the Integrals field are the fitting parameters to that specific measurement. Again, according to equation (1) in the theory of operation section, the sine component represents the X component of the field integral while the cosine component represents the Y component. The X and Y Components field displays the X and Y components along with its polynomial fitting vs. the X position. To

the right are the fitting errors and fitting order. The fitting parameters at a specific X position are shown at the bottom of the plot.
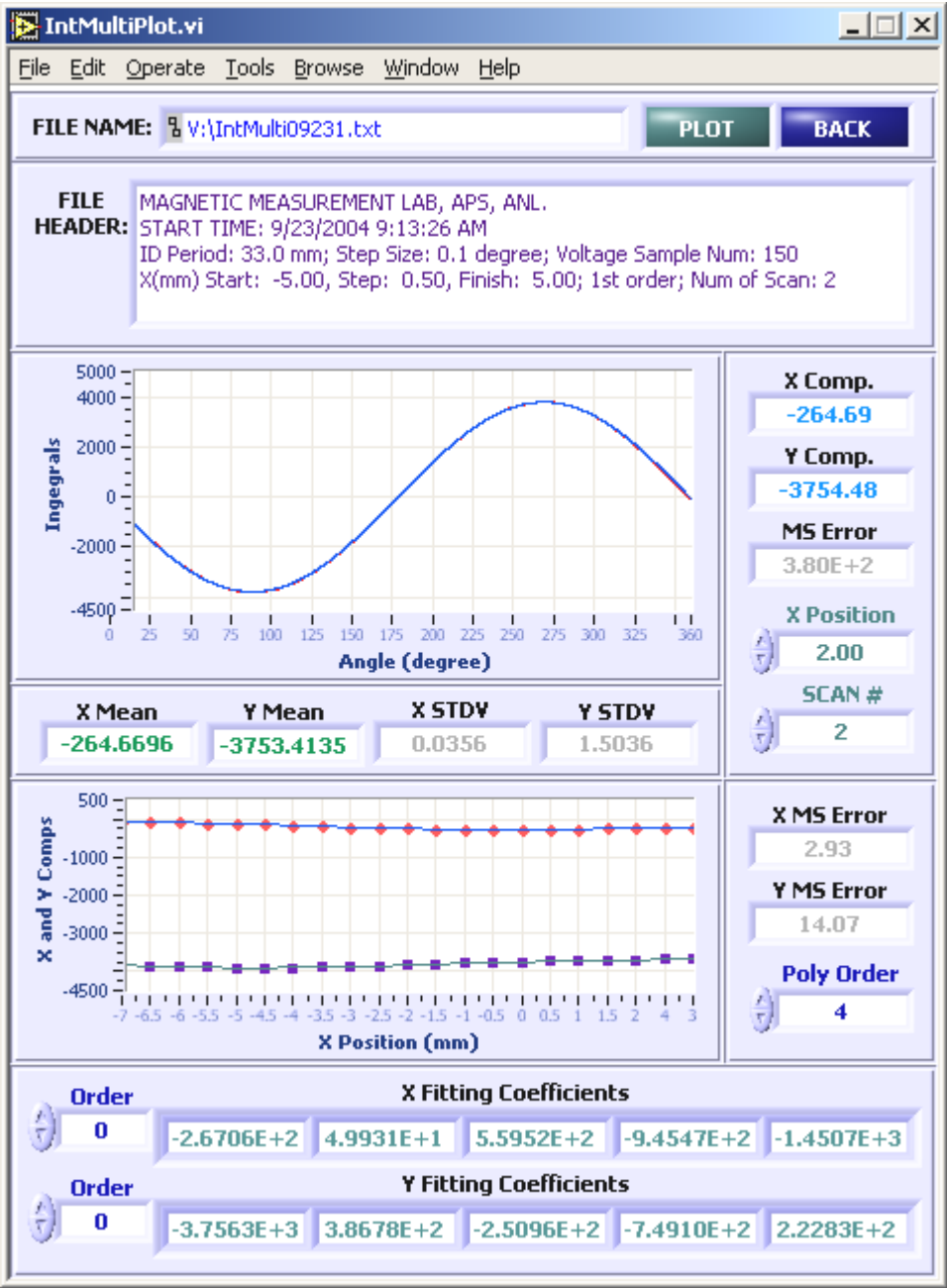

Figure 4. Magnetic field integral multimeasurements.

Figure 5 presents a permanent magnet field integral translation measurement across the X direction. The results are displayed in the Integral Translation Measurement Analysis and Plot submodule. Again, the File Header field shows the basic parameters of the

measurement. The Integral plot field shows a specific integrated raw scan along with its polynomial fitting across the X position vs. the X positions. To the right and the bottom of the Integrals field are the fitting parameters to that specific measurement. The integral signals vs. the X positions are ruled by the equation (3) in the theory of operation section. The Flux Average field shows the average of the multiple raw scans along with its polynomial fitting across the X position vs. the X positions. To the right and the bottom of the Integrals field are the fitting parameters at the specific X position. The wiggled tail was caused by the coil vibration.
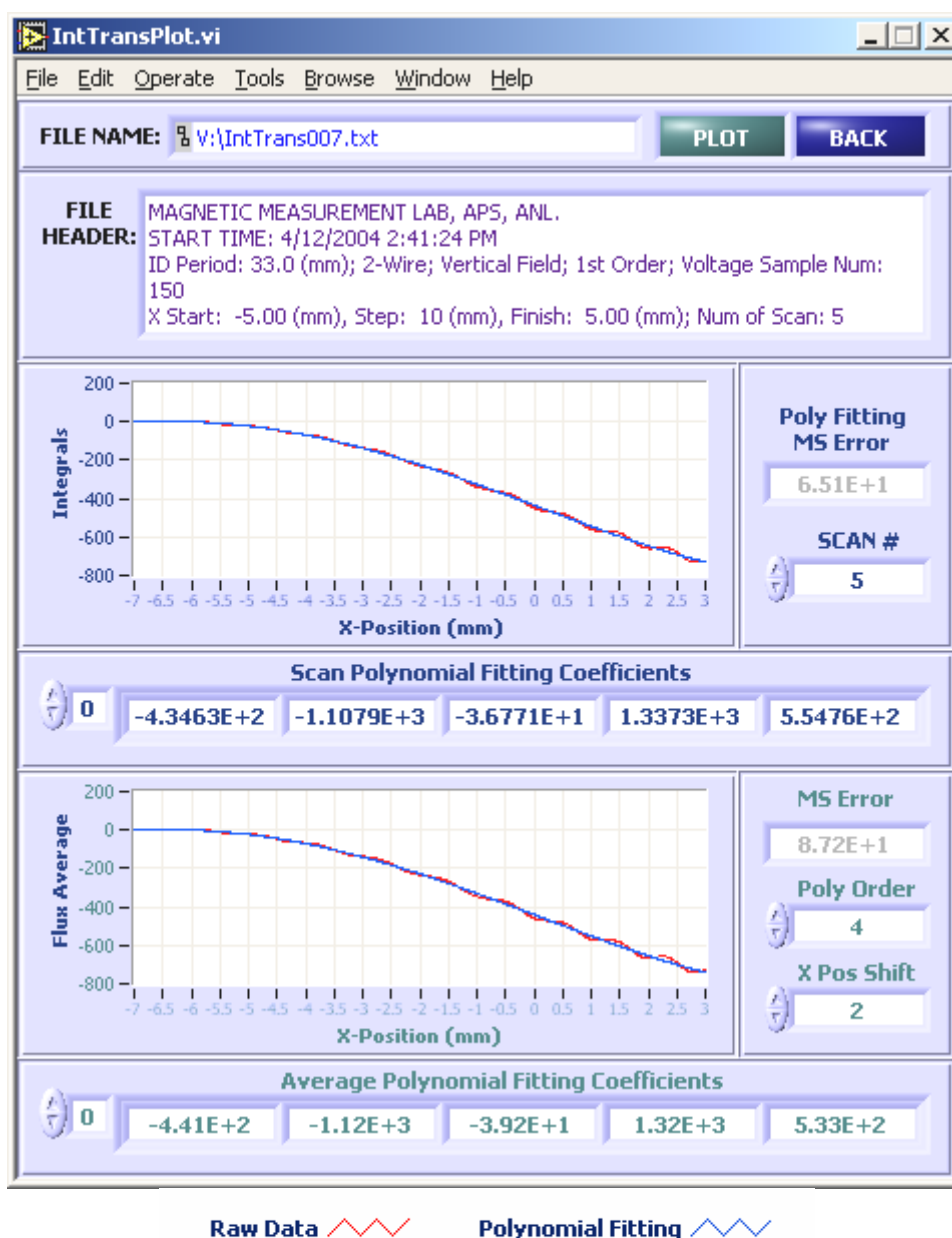

Figure 5. Field integral translation measurements.

6. Conclusion

A new stretched coil magnetic field integral measurement system has been constructed, tested, and commissioned at the Advanced Photon Source. With the latest state-of-the-art field programmable gate array (FPGA) technology, the system achieves the world's highest system measurement accuracy of 0.15 G-cm in the Earth-field integral measurement of 600 G-cm.

Acknowledgment

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